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ORIGINAL PAPER

Regional differences of water conservation in Beijing's forest ecosystem

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Abstract: The water conservation capacities of main forests in Beijing, China were estimated through the quantitative analysis. Various methods developed in published papers on forest hydrology were employed. The forests in Huairou, Yanqing, Miyun, Mentougou and Fangshan districts are the main contributors to water conservation (the cumulative ratio reaches 65%), and the forests in Tongzhou, Chaoyang, Shunyi and Daxing districts have the highest water conservation capacity (3000 m^3/ha). Altitude and slope are the key factors to affect the water conservation capacity. The forests located in Plain Area, Hilly Area, Low Mountain, and Middle Mountain contributes 27%, 28%, 24% and 21% of the conserved water, respectively. The water conservation capacity of forests in Plain Area (2 948 m^3/ha), is superior to the forests in other regions. And the forests situated on Flat Slope, Moderate Slope and Gentle Slope constitute the largest proportion (nearly 93%) of water conservation, while the forests on Flat Slope has the highest water conservation capacity (2 797 m^3/ha), and the forest on Steep slope has the lowest water conservation capacity (948 m^3/ha).

Keywords: forest ecosystem; regional difference; water conservation; Beijing

Introduction

Under the scenario of global climate change, the hydrological role of forests has attracted considerable attention from the public (Bonell 1993; Black 1998; Andréassian 2004). However, the perception that forest is necessary and always good for the water environment has been questioned by the scientific community for a long time (Calder 2007). The practical role of the forest or reforestation in water regulation and soil erosion has been debating vigorously (Zhang et al. 2004; van Dijk and Keenan 2007). Therefore, the potential contribution of a forest to water resources requires special attentions in the area with limited water resources (Zhang et al. 2008).

Since the 1950s, the annual precipitation in Beijing has shown a remarkable decline tendency (Yue 2007), while the municipal water demand has increased dramatically (Wu and Zhang 2005). The severe shortage of water resources has affected the economic and social development of Beijing. However, the area of forest lands in Beijing has increased by 20.2% from 2000 to 2005 (Beijing Statistical Bureau, 2006). Although can produce a substantial number of goods and services for humankind (Pearce 2003), forests may also result in counter-effect. For example, the afforestation can decrease the surface water generation and ground water recharge in many situations. Therefore, forest expansion in the areas with poor water resources should be carefully controlled (van Dijk and Keenan 2007).

In an arid area (excluding high mountains in arid zones), the water yield would decrease significantly with the increase of forest coverage rate (Shen and Wang 2001), since the forests will consume a large amount of water for evapotranspiration. In this context, the hydrological role of forests in Beijing has aroused great concerns from scientists (Gao and Wang 1993; Zhang et al. 1994; Wan and Chen 2000; Liu et al. 2003a; Li et al. 2004; Zhang et al. 2008). However, these are very few studies on the spatially heterogeneous characteristics of the forest ecosystem function for water conservation. Bi and Ge (2009) analyzed the vegetation water conservation effect and its spatial distribution in the Jinghe River basin of the Loess Plateau, by using GIS techniques and giving consideration of the factors (landform and soil). This paper makes an attempt to elucidate the regional variations of the forest ecosystem function on the water conservation in Beijing, and provide some useful information for the conservation of the forest resources in Beijing and other regions with the similar problem.

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Materials and methods

Study Area

Beijing (39°28′–41°05′N, 115°25′–117°30′E), locates in the northern edge of the North China Plain. It has a varied topography, where mountains account for 62% of the surface area. The administrative area of Beijing is 16 807 km^2, and is composed of four city districts (Xuanwu, Chongwen, Xicheng, and Dongcheng), four suburb districts (Shijingshan, Chaoyang, Haidian and Fengtai) as well as ten outer suburbs or rural counties (Daxing, Fangshan, Mentougou, Changping, Yanqing, Huairou, Miyun, Shunyi, Pinggu and Tongzhou). According to the survey data of the forest resource in 2004, Beijing's forest ecosystem had a total area of 940,701 ha, of which 14.61% was covered by the coniferous forest, 43.85% by the broadleaved forest, and 7.36% by the broadleaved-coniferous mixed forest. The remaining 34.17% were shrub forests. The average volume per hectare was 28.47 m^3, and the forest coverage rate reached 35.47%. These forests were mainly distributed in three regions, i.e. the west mountain area at the north part of the Taihang Mountain range, the north mountain area of the Yanshan Mountain range, and the southeast plain area which is the main agriculture region with almost no natural vegetation. The dominant tree species include *Quercus dentasa, Platycladus orientalis, Pinus tabulaeformis, Robinia pseudoacacia, Populus davidiana, Betula platyphylla, Larix principis-rupprechtii*, and so on, in which a rich variety of other species of fauna and flora are hosted.

Research methods

The term "water conservation" has various interpretations by different scientists (Zhang et al. 2009). In this study, we defined "water conservation" as the rainfall interception service through canopy interception, floor retention and soil water storage. From the water balance perspective, the imported water into a forest ecosystem should be to the sum of conserved water and lost water through evapotranspiration and streamflow (Liu et al. 1996). Based on the water balance principle, the conserved water (Q) in a forest ecosystem can be estimated by the following equation:

$$Q=10*(R-E-C)*A \tag{1}$$

where R is the annual precipitation (mm), E is the annual evapotranspiration (mm), C is the amount of surface runoff (mm), and A is the forest area (ha).

Usually, the water conservation capacity of a forest is summed over canopy interception, floor retention and soil water storage. If we can determine the maximum interception capacities of forest canopy, floor and soil, then the maximum water regulating capacity of a forest sublot (W_i) can be approximated by the empirical model of forest canopy interception (C_i), floor retention (L_i) and soil water storage (S_i) as follows:

$$W_i = C_i + L_i + S_i \tag{2}$$

The intercepted rainfall by canopy depends on the precipitation condition and canopy interception rate, which is closely related to forest type, canopy density and leaf area index (Wen and Liu 1995). Owing to the alternative occurrence of rainfall interception and evaporation, the water intercepted amount in the largest rainfall event represents the potential water regulating capacity of forests better than the total water amount in a year (Zhang et al. 2010). Therefore, C_i can be determined by the following equation:

$$C_i = \sum_{i=1}^{n} 10 * \alpha_i * R_{\max} * A_i \tag{3}$$

where, α_i is the canopy interception rate (%) and showed in Table 1, $R_{\max}$ is the precipitation of the largest rainfall event in a year (mm).

Table 1. The canopy interception rates of forests in Beijing

Forest type	Dominant tree species	Interception rate [a] (%)
Coniferous forest	*Pinus tabulaeformis*	24.95[b]; 30.95[c];14.82[d]; 23.96[e];23.83[f]
	Platycladus orientalis	23.35[c];22.29[f]
	Larix principis-rupprechtii	23.62[f]
	Average value	23.38
Broad-leaved forest	*Robinia pseudoacacia*	17.37[f];18.36[b]
	Acer truncatum	19.25[f]
	Q.liaotungensis	20.40[g];16.26[h]
	Castanea mollissima	19.14[b]
	Tilia	19.38[f]
	Average value	18.79
Coniferous and Broad-leaved Mixed forest	Deciduous broad-leaved tree	16.5[g];21.37[f];18.65[h]
	Pinus tabulaeformis and Acer truncatum	26.38[f]
	Average value	22.61
Shrub forest	*Scrub.Vitexnegundovar.heterophylla*	23.57[c]
	Spiraea triloba	21.53[c]
	Average value	22.55

[a] derived from the arithmetic average value of the interception rates in referred literatures; [b] Liu et al. (2003); [c] Zhang et al.(1994); [d] Yu et al.(2004); [e] Xiao et al.(2007); [f] Li (2007); [g] Li et al.(1997); [h] Wan et al.(1999).

The contained water of forest floor depends largely upon the thickness of floor layer and its maximum water-holding capacity. The forest floor retention (L_i) can be estimated by

$$L_i = \sum_{i=1}^{n} \delta_i * d_i * A_i \tag{4}$$

where, δ_i is the water-holding capacity of floor ($t \cdot cm^{-1} \cdot ha^{-1}$) and showed in Table 2, d_i is the thickness of floor (cm).

Table 2. The water-holding capacities of forest floor in Beijing

Forest type	Dominant tree species	Water-holding capacity [a] ($t \cdot cm^{-1} \cdot ha^{-1}$)
Coniferous forest	*Pinus tabulaeformis*	9.33[b];6.62[c];12.61[d]
	Platycladus orientalis	14.5[b];7.33[c];14.18[d]
	Larix principis-rupprechtii	9.47[c];10.29[e];10.61[d]
	Average value	10.55
Broad-leaved forest	*Robinia pseudoacacia*	9.39[c];9.4[e];29.36[d]
	Populus davidiana	6.39[c];9.6[e]
	Betula platyphylla	9.15[c];9.81[e]
	Acer truncatum	15.56[d]
	Tilia	16.08[d]
	Average value	13.03
Coniferous and Broad-leaved Mixed forest	*Deciduous broad-leaved tree*	16.83[d];9.11[c]
	Pinus tabulaeformis and *Acer truncatum*	15.62[d]
	Average value	14.30
Shrub forest	*Scrub.Vitexnegundovar.heterophylla*	4.59[b]
	Spiraea triloba	7.52[b]
	Average value	6.06

[a] derived from the arithmetic average value of the water-holding capacities in referred literatures; [b] Zhang, et al.(1994); [c] Yu, et al.(2004); [d] Li(2007); [e] Gao, et al.(1993).

The amount of (static) water stored in a forest soil has a close correlation with the capillary porosity and the soil depth (Jia et al. 2005), and the soil water storage depends largely on the soil non-capillary pore (Liu et al. 2003b). In this paper, we focus on the potential capacity of water storage, therefore the roles of the soil capillary and non-capillary porosity of forest should be taken into account. Table 3 shows the capillary and non-capillary porosity of the soil in Beijing. Thus, the soil water storage (S_i) can be estimated by the following equation:

$$S_i = \sum_{i=1}^{n} \gamma_i * h_i * A_i \tag{5}$$

where γ_i is the total soil porosity (%) and can sum from the capillary porosity and the non-capillary porosity, h_i is the depth of the soil layer (cm).

The forests in Beijing area are very heterogeneous in terms of forest type, tree specie, soil property, slope location, and so on. On the basis of Category II of the sixth Beijing forest resources data, a spatial database was developed for exploring the relations between the 96,501 forest sublots and their capacities for water conservation. If the total amount of conserved water in a forest ecosystem and the maximum capacity of the water conservation of each forest sublot could be calculated, the amount of conserved water in each forest sublot (WQ_i) can estimated by Equations (6).

$$WQ_i = W_i * Q / \sum_{i=1}^{n} W_i \tag{6}$$

Table 3. The capillary porosity and non-capillary porosity of forest soil in Beijing

Forest type	Dominant tree species	Capillary porosity [a] (%)	Non-capillary porosity [a] (%)
Coniferous forest	*Pinus tabulaeformis*	39.34[b]; 42.7[c]; 44.37[d]; 42.1[f]	9.85[b]; 9.8[c]; 10.72[d]; 5.4[f]
	Platycladus orientalis	42.8[g]; 35.69[b]; 40.92[d]; 42.6[f]	18.2[g]; 9.69[b]; 10.78[d]; 10.0[f]
	Larix principis-rupprechtii	44.09[e]; 45.27[d]; 42.1[f]	6.9[e]; 9.07[d]; 8.1[f]
	Average value	42.15	9.71
Broad-leaved forest	*Poplar*	30.70[h]	15.40[h]
	Quercus variabilis	43.90[c]	8.50[c]
	Robinia pseudoacacia	43.67[d]; 44.02[e]; 43.6[f]	7.95[e];12.18[d];7.4[f]
	Betula platyphylla	54.68[e]	10.85[e]
	Populus davidiana	60.25[e]	8.96[e]
	Acer truncatum	45.82[d]	10.41[d]
	Tilia	48.34[d]	10.91[d]
	Average value	46.78	11.36
Coniferous and Broad-leaved Mixed forest	*Pinus tabulaeformis* and Acer truncatum	50.6[c]; 44.26[d]	6.8[c];12.34[d]
	Deciduous broadleaf tree	47.8[f]; 47.37[d]	10.5[f];12.25[d]
	Average value	47.51	10.91
Shrub forest	*Lespedeza* and *Scrub. Vitexnegundovar. heterophylla*	42.20[b]	8.68[b]

[a] derived from the arithmetic average value of the soil porosities in referred literatures; [b] Zhou(1996); [c] Wu, et al.(2002); [d] Li(2007); [e] Gao, et al.(1993); [f] Yu, et al.(1999); [g] Jia, et al.(2005); [h] Liu(2007).

In the Forest Resource Database of Beijing on WebGIS, the characteristics (e.g. land type, tree specie, soil depth, slope degree, and so on) of the forest sublots determine the ‘strength’ of water conservation. Therefore, we can determine the spatial distribution of water conservation function based on the attributions and locations of the forest sublots.

Results and discussion

Though the water balance method is limited by the accuracy problem, it is still regarded as an effective way to estimate the amount of water conserved in a forest ecosystem (Sun and Zhu 1995). The annual mean precipitation was 483.3 mm in 2004 (Beijing Statistical Bureau, 2006), the multi-year average annual evaportranspiration rate was 67% (He 1986; Li and Chen 1997), and the average depth of surface runoff was 19.41 mm between June and September in 2004, based on the observations from the long-term fixed positions for the forest ecosystems in Beijing. Therefore, we can estimate that Beijing's forest ecosystem could conserve 1.32×10^9 cubic meters of water by using Eq.1, and the average amount of water conserved is 1 404.27 m^3/ha. Based on the analysis to the precipitation characteristics in Beijing from 1950 to 2005 (Sun et al. 2007), the precipitation of the largest rainfall event can be assumed to be 100 mm (R=100). Thus, the amount of water conserved in each forest sublot can be calculated by Eqs.(2)-(6).

The water conservation of the forests at different districts

According to the survey data obtained in 2004, the forest area of Huairou, Miyun, Yanqing, Mentougou, and Fangshan districts added up to 73%. The total forest area of Changping, Pinggu, Daxing, Shunyi, and Tongzhou districts accounted for 23%. The amount of water conserved in forest ecosystem depends largely on its area and water conservation capacity. Results showed that, the forest of Huairou conserves approximately 2.23×10^8 cubic meters of water, accounting for 17% of the total conserved water. The forests of Yanqing, Miyun, Mentougou and Fangshan districts store 1.99×10^8 cubic meters, 1.57×10^8 cubic meters, 1.43×10^8 cubic meters, and 1.31×10^8 cubic meters of rainfall, respectively, and are corresponding to 15%, 12%, 11% and 10%. Therefore, the forests of Huairou, Yanqing, Miyun, Mentougou and Fangshan districts are the main contributors to the water conservation (the cumulative ratio reaches 65%). However, the mean capacity of water conservation is greatly different. The forests in Tongzhou, Chaoyang, Shunyi and Daxing districts have the highest water conservation capacity (3000 m^3/ha), mainly due to the fertile soil layer. The water conservation capacities of forests in Fengtai, Haidian, Pinggu and Shijingshan districts range from 2 000 m^3/ha to 2 700 m^3/ha, and the forests in Yanqing, Changping, Huairou and Mentougou have the lower water conservation capacities (Fig.1).

The water conservation of forests at different elevation

According to the altitudes of forests in Beijing area, four zones can be defined, including Plain area (elevation below 100 m), Hilly area (elevation range 100-500 m), Low mountain (elevation range 500-800 m), and Middle mountain (elevation above 800 m). The forests mainly distributed in Hilly area account for 32% of the total forest area, while the forest in Low mountain, Middle mountain, and Plain area cover 29%, 23% and 16%, respectively. Fig. 2 shows the amount of conserved water and the water conservation capacity of forests in different altitudes. It can be observed that the forest located in Plain area conserves 3.52×10^8 cubic meters of water, which is 27% of the total amount of conserved water. The forests in Hilly area and Low mountain store 3.73×10^8 cubic meters and 3.22×10^8 cubic meters of water, which contribute 28% and 24% of the total water amount, respectively. The forest in Middle Mountain conserves 2.73×10^8 cubic meters of water which accounts for 21% of the conserved water. However, the forest in Plain area conserves 2948 m^3/ha of water, which is superior to the forests in Hilly area, Low mountain and Middle mountain with a mean capacity of 1 550 m^3/ha.

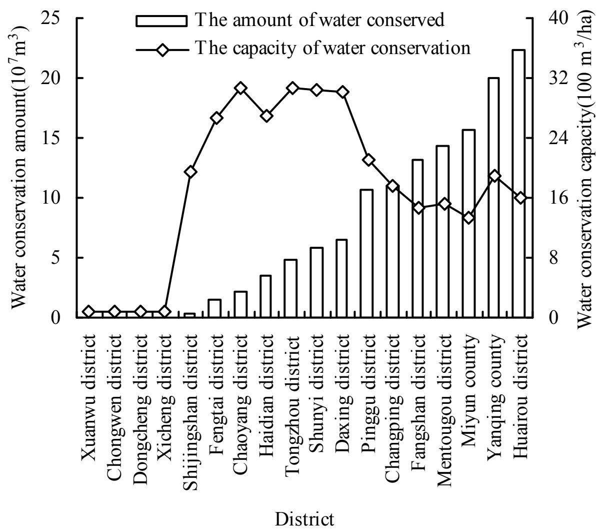

Fig. 1 The water conservation of the forests in different districts

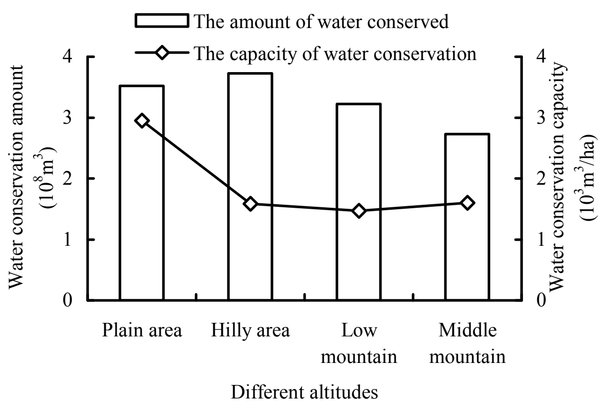

Fig. 2 The water conservation of the forests at different elevations

The water conservation function of forests at different gradients

The debris flow disaster in mountain area has been seriously threatened the sustainable development in Beijing (Xie, et al., 2004), and the hydrological role of forests under different slope gradients has attracted more and more attentions. In this study,

the forest region in Beijing could be divided into five classes, including Flat slope (≤ 5°), Mild slope (5–15°), Gentle slope (15–25°), Moderate slope (25–45°) and Steep slope (≥45°). According to the survey data of Beijing's forest resources, the forest area of Moderate slope, Gentle slope, and Flat slope covers 45%, 25%, and 23% of the total forest area, respectively. However, the forest on Flat slope conserves 4.71×10^8 cubic meters of water, which provide the largest proportion of the total amount of conserved water (approximately 36%). The forest on Moderate slope stores 4.64×10^8 cubic meters of water, which accounts for 35%. The contributions of forests on Gentle slope, Mild slope and Steep slope to the water conservation are relatively low. Thus, the forests situated on Flat slope, Moderate slope and Gentle slope constitute the largest proportion of water conservation in Beijing's forest ecosystems (nearly 93%). In addition, the forest on Flat slope has the highest water conservation capacity (2 797 m^3/ha), and the forest on Steep slope has the lowest water conservation capacity (948 m^3/ha).

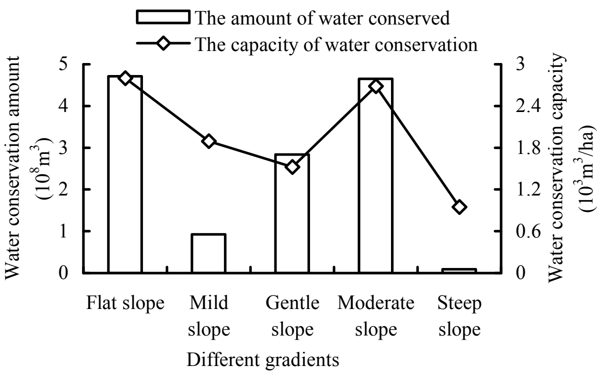

Fig. 3 The water conservation of the forests at different gradients

Conclusion and discussion

In recent years, the water crisis in Beijing has significantly restricted the sustainable development of economy and society, how to realize the hydrological roles of forests in Beijing has become a hotspot. On the basis of forest resource survey data and mathematical simulations, we analyzed the water conservation of forests in different regional locations in Beijing. The results showed that, the forests of Beijing could conserve 1.32×10^9 cubic meters of rainfall, and the water conservation function among forests located in different regions shown significant variations. In the past, people usually paid more attentions to the extension of forestland area, and neglected the spatial variations of water conservation of these forests. The study contributes to understanding the hydrological role of forests in Beijing.

The processes of water conservation in a forest ecosystem are complicated. Although this study discussed the regional variations of water conservation of forests in different districts, elevation and gradients, it has such drawbacks as spatial heterogeneity of precipitation and evaporation were neglected, the forest stand structure and forest growth in regulating ecohydrological functions were also discriminated. More observation and experimental data in term of canopy interception and litter biomass, and soil properties are needed. Therefore, the long-term fixed position observations on the hydrological roles of forest ecosystem should be carried out in more locations to provide basic information. Furthermore, more attention should be paid to the modification and improvement of such empirical models as the water balance method, the precipitation interception of the forest canopy and the evapotranspiration models.

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